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REVIEW

Compensating inherent linear move water application errors using a variable rate irrigation system

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Abstract Continuous move irrigation systems such as linear move and center pivot irrigate unevenly when applying conventional uniform water rates due to the towers/motors stop/advance pattern. The effect of the gear drive/cart movement pattern on linear move water application is larger on the first two spans, which introduces errors on site-specific irrigation. Therefore, the objectives of this study were to model the linear move irrigation system cart movement and to develop an algorithm to compensate for unintended variable irrigation (application errors). The cart advance/movement modeling considered terrain attributes, average nozzle travel speed, and high frequency DGPS (differential global positioning system) cart positioning readings. This paper describes the use of an irrigation monitoring and control system, DGPS, GIS, and statistical analysis utilized in the modeling and compensation processes. The irrigation monitoring and control system was composed of a single board computer, a relay board controller, DGPS, electric solenoid valves, wireless ethernet bridge units, high frequency spread spectrum radios, as well as in-line and in-field sensor networks. This technology allowed for continuous, real-time data acquisition and irrigation system management through the internet. This study has shown that irrigation application errors were reduced from over 20% to around 5%, in the subsequent irrigation event.

Keywords Site specific irrigation · Linear move irrigation advance pattern · Water application coefficient of uniformity · Water application distribution uniformity

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Introduction

Applying uniform amounts of water over agricultural fields with uniform soil characteristics and variable application over fields containing variable soil types is highly desirable in order to maximize yields and nutrient consumption. It also protects the environment from fertilizers/chemicals lixiviation down the root zone and into groundwater; in other cases to avoid localized soil salinization due to under irrigation. Under irrigation can occur when the irrigation system consistently applies smaller amounts of water than the crops need in certain areas of the field.

The errors or variability in applying "uniform" water rates using linear move (LM) irrigation systems, with sprinklers, have been reported to be 13–23%, with coefficient of uniformities in the order of 81–89% (Hanson et al. 1984). Hanson (2005) indicates that potential maximum irrigation efficiencies for continuous move systems (sprinkler heads) range from 80 to 90%. Generally, center pivots (CP) have lower application efficiencies, i.e., around 80%, while LM systems have better efficiencies, around 90%. Fraisse et al. (1995) reported a coefficient of uniformity exceeding 90% when using pulsing nozzles on a LM system at a frequency of 1 cycle per minute and a percent timer setting at <50%.

It is known that the intermittent LM gear drive and tower movement contributes to the water application variability along the LM pathway in the crop field. Hanson and Wallender (1986) pointed out that although CP and LM are classed as continuous move machines, in reality, they move in a series of starts and stops sequence, being the movement of one tower different from the others. Thus, uniformity of the water applied may depend on a particular start/stop sequence. Also, variation in actual speed, other than percent timer setting, can be attributed to slippage and coasting of the towers after control relays opened (Fraisse et al. 1995). However, in the last decade new monitoring and control systems have been developed for continuous move irrigation systems. These systems allow for the monitoring of water pressure/flow in the main pipe (and/or manifolds) as well as the positioning of the LM by ways of a DGPS (differential global positioning system) unit(s). The control part of the system has to do with the ability to control the opening (On/Off, pulsing) of individual or group of nozzles/sprinklers by location in the field. Chávez et al. (2009a, b) described such a system and demonstrated the system capability to adequately control pulsing along the LM line and in the direction of travel that may help increase application uniformities by compensating for the cart stop/advance pattern water application errors.

This paper models the sources of uniform water application errors (common but inappropriate) for a LM and describes a methodology to compensate for those errors using a variable irrigation control and monitoring system.

Materials and methods

A four-span LM system was used at the Washington State University (WSU), Center for Precision Agricultural Systems (CPAS) in Prosser, WA. This system was equipped with a remote irrigation monitoring and control system (RIMCS), detailed in Chávez et al. (2009a). Three lines of catch cans were set up in a 3 × 3 m grid along the path way of the system. The cans were located under the first span and more precisely between the path way of nozzles 3, 4, 5, and 6 (Figs. 1, 2). The field (H11) has a longitudinal length of 120 m with an average longitudinal terrain slope of 5% (north–south). According to Keller and Bliesner (1990), linear-moving machines are restricted to operating on long, smooth to gently rolling fields with slopes of not more than 2–3% in the direction of travel and 1–1.5% along the lateral. Thirty-three rows of catch cans spanned over 96 m out of the 120 m. A full description of the LM system can be

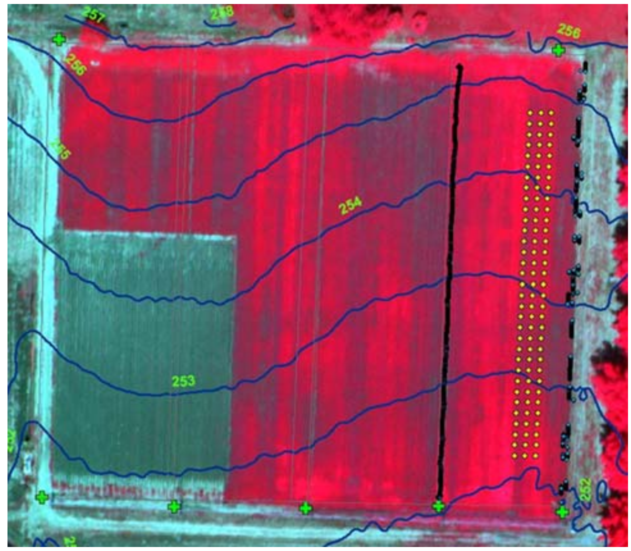

Fig. 1 H11 field at WSU-CPAS showing catch can positions (three *parallel lines* of *small circles*) along the travel path of the first span of the WSU-CPAS LM irrigation system

Fig. 2 Pierce mini-LM irrigation system in field H11 passing over a catch can grid

found in Chávez et al. (2009a). Catch can tests were performed following the guidance by ASABE (2007), Keller and Bliesner (1990), and Merriam and Keller (1978).

The catch can data were analyzed using descriptive statistics, mean bias errors (mbe), root mean square errors (rmse), and the Christiansen coefficient of uniformity (CUc) described in details in Christiansen (1942). Other authors have tried to identify how the water application variability occurs using autocorrelation and spectral analysis (Hanson et al. 1984).

There were nine irrigation tests in May 2006 with full application rate at different percent timer (PT) settings and one with variable irrigation in June: 05/11 (20% PT), 05/12 (30% PT), 05/16 (40% PT), 05/26 (40% PT), 05/27 (30% PT), 05/29 (20 and 70% PT), 05/30 (20% PT), and 06/09

(30% PT). There were repetitive (3) PT settings in order to verify the water application error location along the LM path way (replicas).

The WSU RIMCS utilizes a DGPS Garmin 16 LVS unit to locate the LM cart position in the field. GPS data were collected at a frequency of 1 Hz and used to compute 1 min nozzle travel speed over a distance of 10 m, the sprinkler nozzle wetted diameter.

The 10-m distance was chosen since the sprinkler/nozzle water droplets start hitting the catch can when the nozzles are 5 m from the collector position and stops hitting it when they are 5 m (nozzle wetted radius) pass the collector location.

According to Heermann and Stahl (1986), the coefficient of uniformity is more a function of the sprinkler pattern radius and arc lengths than the magnitude of the alignment angle.

The 1-min nozzle travel speeds were averaged over 10-m segments, where the catch can was located in the middle of the segment. These average travel speeds were correlated to the catch cans water volume/depth and to ground elevation in order to explain errors in the water application along the travel path of the span. It is worth highlighting the importance of accurate GPS readings in this process. Heermann et al. (1997) discussed the position reporting alternatives and concluded that GPS was the most viable method for determining field position for lateral move systems. Peters and Evett (2005) investigated the accuracy of low-cost GPS units as applied to center pivots or lateral move irrigation systems and found that significant improvement of angular position reporting was possible and that the test of low-cost receiver was accurate to within 2.1 m, 95% of the time. However, the remaining 5% of points had errors as large as 6.6 m. Chávez et al. (2009b) found out that the DGPS Garmin 16 LVS unit positioning error was 2.5 ± 1 m.

Results

Figure 3 shows the linear distribution of water applied at a PT of 20 [both upper lines, Northing vs. Can Line 1 (closed circles) and Line 2 (open circles)] and the 1-min average nozzle travel speed (v) along the LM travel pathway (lower spiky line). The variability in the volume of water captured by the catch cans by location, from 60 to about 110 ml, and for "v" from zero to about 5.5 m min^{-1} is evident. No apparent cart movement pattern is seen in Fig. 3. Location or position was defined by the GPS Northing (m) readings in the UTM (Universal Transverse Mercator) projected coordinate system. The UTM zone was 11 north and the datum NAD83.

An exponential dependency of the nozzle travel speed with ground elevation was found, R^2 of 0.7 (Fig. 4). The higher the elevation the lower the average nozzle travel speed. The correlation shown in Fig. 4 is only valid for the LM traveling north. The LM traveled in the northern direction, i.e., uphill on an average 5% grade pulling a 80-m long, 0.102-m (4″)-diameter P.E. hose that may have contributed to the system slippage and lower speeds toward the northern end of the field. Fraisse et al. (1995) observed that the change in dragged length of the feed hose affects the speed by as much as 15%.

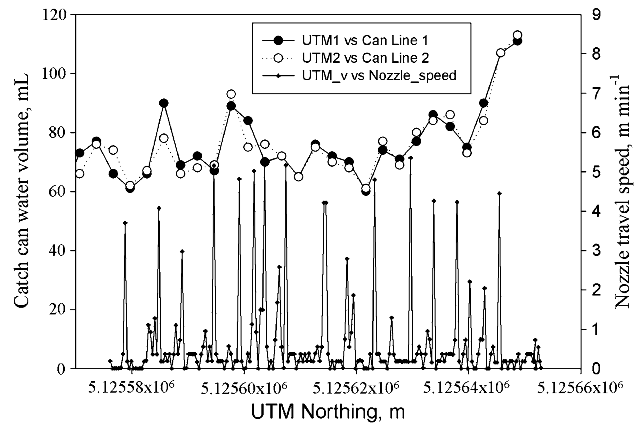

Fig. 3 Catch can water volume and 1-min average nozzle travel speed variability

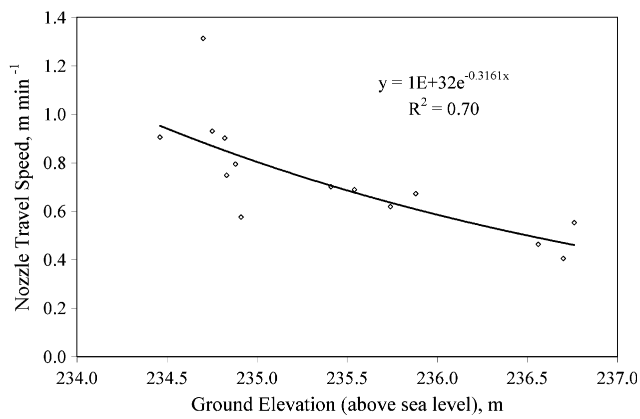

Fig. 4 Ground elevation versus nozzle travel speed for a 20 PT

Figure 5 illustrates the positioning of a catch can in a 10-m segment, distance in which the 1-min nozzle travel speeds were averaged. A large variability in nozzle speed occurs in the 10 m where water was sprinkled into the collectors at a PT setting of 20%.

The nozzle travel speeds (v) averaged over 10-m segments were compared with the water collected in the 33 catch cans along the pathway of the LM. The comparison is seen in Fig. 6 where the depth of water applied, for a PT of 40, is shown in the upper curve (Can Line 2, open circle symbols), the average nozzle travel speed in the lower curve (plus symbols) and the target water depth as a straight line (Ht, closed circles).

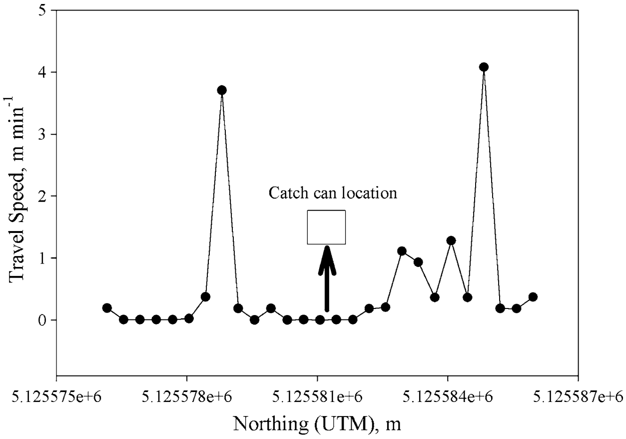

Fig. 5 Nozzle travel speed variability by location for a PT setting of 20%. Catch can centered at 5,125,582.7 m, UTM Northing

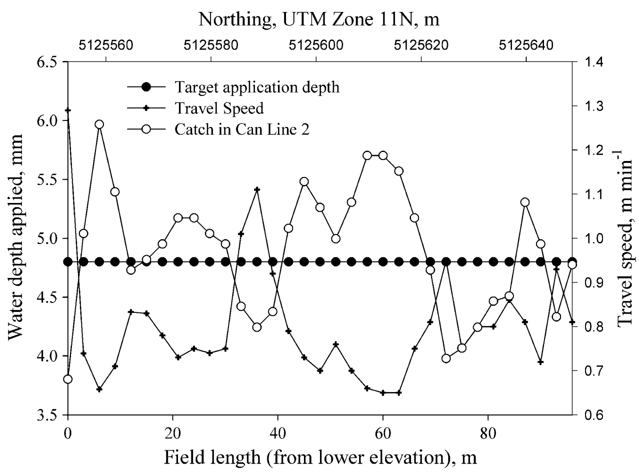

Fig. 6 Comparison of water depth applied with nozzle travel speed by location

Figure 6 shows lower application for higher speeds and higher applications for lower speeds, by position, therefore resulting in under irrigation in same locations of the field and over irrigation (related to target values) in other locations in the field.

Table 1 compiles the average statistics of four irrigation test events. In Table 1, the coefficient of variance, the rmse, and the CUc, in general, show that at a lower PT setting the water application uniformity increases (smaller errors) in accordance with Fraisse et al. (1995) findings; who stated that application uniformity values generally increase with increased pulsing duty cycle and decreased timer setting. The exception was the result from the 70 PT test; where the uniformity was comparable to the 20 PT setting.

Nozzle travel speed variation (dv%, error in percent) was calculated by comparing the nozzle travel speed (v) to the target velocity (vt), i.e., [(observed value − expected value)/(expected value) × 100]. Similarly, water depth application errors (dH%) were calculated using the water depth applied at each catch can and the target water depth (Ht). Ht is a function of the PT setting and the maximum LM travel speed (vx). The “vx” value was determined in the field by recording the time it took the LM to cover field H11 length at a 100% PT. Figure 7 shows the exponential curve relating PT settings to target (reference) water depth

Table 1 Statistics of water applied and nozzle speeds for four different PT settings

Variable	Unit	Percent timer setting (PT, %)			
		20	30	40	70
Date		5/30	5/27	5/26	5/29
H avg	mm	9.9	7.7	4.9	3.3
H std	mm	0.8	0.7	0.5	0.3
H cv	%	7.6	9	11	8.2
H mbe	mm	0.2	0.2	0.2	−0.1
H mbe	%	2.5	2.6	2.1	−2.1
H rmse	mm	0.8	0.7	0.5	0.3
H rmse	%	7.8	9.2	11.1	8.1
CUc	%	93.1	92.6	91.3	93.3
Ht	mm	9.7	7.4	4.8	3.3
vt	m min^{-1}	0.4	0.6	0.8	1.2
vx, 100%	m min^{-1}	2.0	2.0	2.0	2.0
dHx	%	15.8	26.1	24.3	12.5
dHm	%	−13.4	−11.1	−20.8	−16.9
dvx	%	67.5	41.7	62	18.5
dvm	%	−20	−2.5	−18.4	−13.4
U avg	m s^{-1}	1.32	1.94	1.90	1.59

Percent timer (PT), average water depth applied (H), standard deviation of water depth applied (H std), coefficient of variance of water depth applied (cv), target nozzle travel speed (vt), maximum nozzle travel speed at 100 PT (vx), maximum error in H (dHx), minimum error in H (dHm), maximum error in v (dvx), minimum error in v (dvm), and average horizontal wind speed (U avg). The mbe stands for mean bias error and rmse for root mean square error

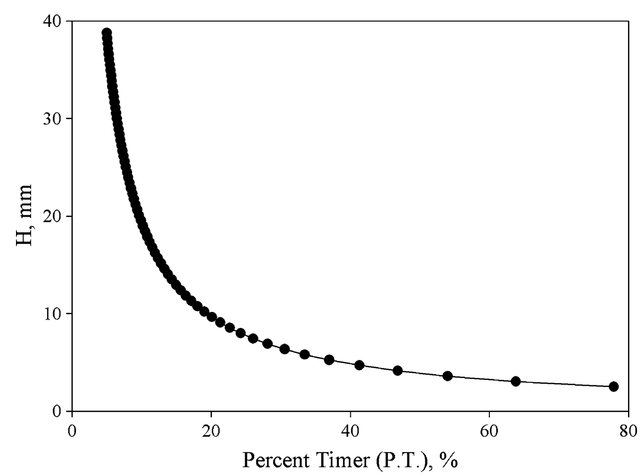

Fig. 7 WSU LM system percent timer (*PT*) versus water application depth (H) *curve*

Table 2 Exponential decay model relating speed variation to water application errors

y = water application error, dH (%), and x = LM gear drive/nozzle travel speed variation, dv (%)

$y = y_0 + ae^{-bx} + ce^{-dx}$

Coefficient	Percent timer (%)			
	20	30	40	70
y_0	1.025E+01	−2.201E+02	−2.303E+03	−1.022E+02
a	−2.718E+00	2.239E+02	7.536E+00	4.897E+01
b	1.724E−12	2.023E+01	6.485E−02	1.038E−02
c	−5.027E+00	1.883E+01	2.295E+03	5.128E+01
d	9.320E−13	4.291E−02	8.135E−05	8.862E−03
R^2	0.70	0.70	0.75	0.74

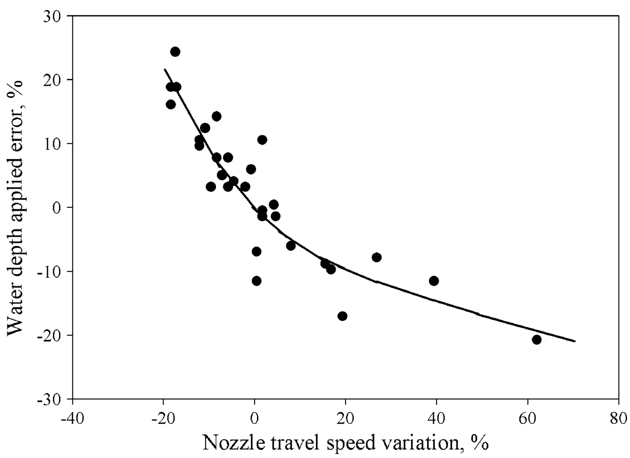

Fig. 8 Nozzle speed errors versus water application errors for the 40% PT

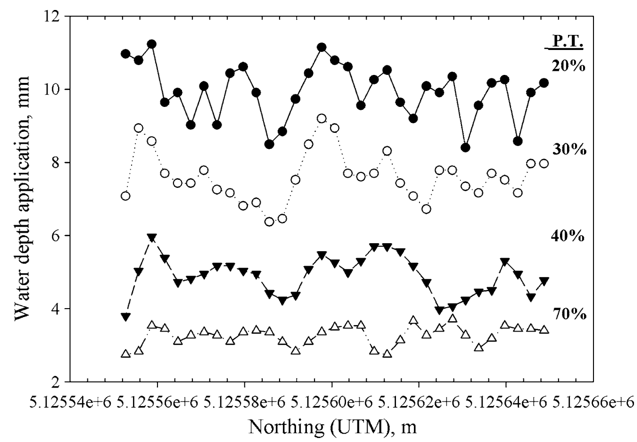

Fig. 9 Water application depths for different PT settings by location in the field

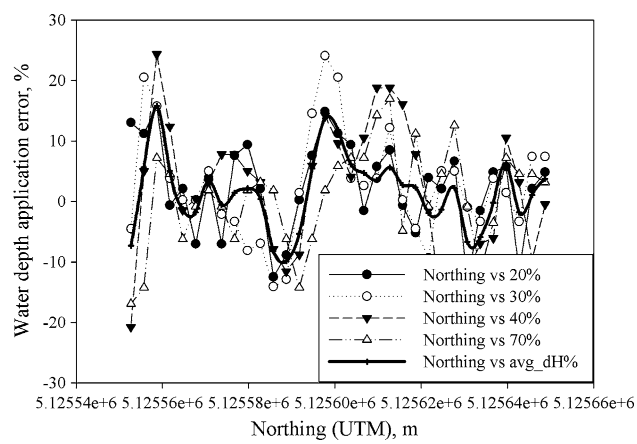

Fig. 10 Water application errors for different PT settings by location in the field

values for the WSU LM system. This curve was developed following Keller and Bliesner (1990) procedure and field observations.

The dv% values were regressed against the dH% values for the four different PT shown in Table 1, in order to determine their dependency. Table 2 summarizes the intercept, slope, and coefficient of determination of an exponential decay type curve (double, five parameters), which relates dv% to dH% with a very good average R^2 of 0.72. Figure 8 shows the plots of dv% versus dH% for the 40% PT and its respective exponential decay model. The model fits the data very well, although the data show some scatter around the origin. The lower negative dH% values at the origin may be explained by the fact that toward the 1/3 end of the field the wind speed increased from 2 to 3 m s^{-1} thus increasing droplet evaporation and drift. The dv% versus dH% errors have a similar curve shape "variation" as the curve shown in Fig. 7, which determines the WSU LM system Ht by a given PT setting.

Figure 9 plots the water application depth by location for the four different PT settings. It is observed that, in general, the high and low water application depths occur in the same location along the LM path; this is in accordance with our earlier findings when repeating the irrigation test event several times for the same PT setting (replicas). This is also an indication that the LM cart movement pattern (stop/advance duration) tends to repeat itself by location. On Fig. 10, the percent errors for water applied by location for different PT are plotted. In general, the errors have similar magnitude by location, from −20 to 25% errors, indicating that the percent errors in water application are independent

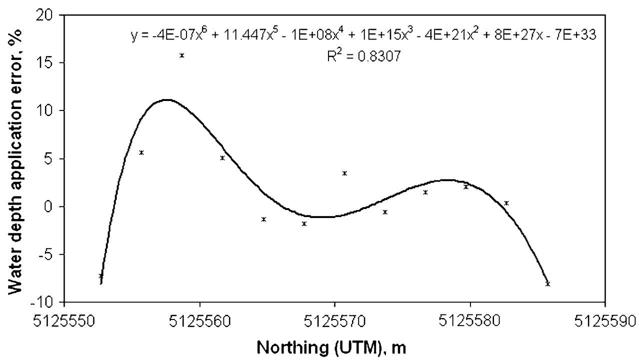

Fig. 11 Water application errors curve fitting by location at the lower field portion

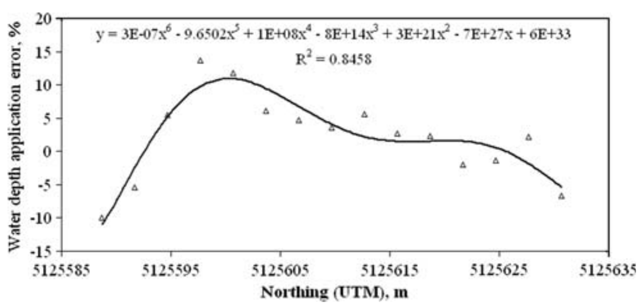

Fig. 12 Water application errors *curve* fitting by location at the upper field portion

of PT settings and rather a result of the LM cart movement pattern. As depicted by the trend that seems to occur every 40 m (repetitiveness), i.e., from UTM Northing position 5,125,550 to 5,125,590 m and from the latter to the 5,125,630 m.

All four water depth application error curves (corresponding to the 20, 30, 40, and 70% PT) were averaged, and the resulting values were plotted as an average error line (darker line, called Northing vs avg_dH%) in Fig. 10.

Hanson et al. (1984) found periodicity in the volume of applied water by both center pivots, when analyzing the data using autocorrelation and spectral analysis, and it seems that our data show a similar behavior for the WSU LM system. Therefore, we divided the avg dH% data set into two data sets in order to fit a curve, being the data split at the 5,125,590 m position. Figures 11 and 12 show the result of fitting a six degree polynomial curve into these data. The data corresponding to the lower portion of the field showed an R^2 of 0.83 while the R^2 for the upper portion was 0.85.

Once the application percent errors were characterized by location, we changed their signs, i.e., negative errors became positive values and positive errors became negative values. These new values were called correction values and were introduced in the “mapfile” of the WSU LM RIMCS system.

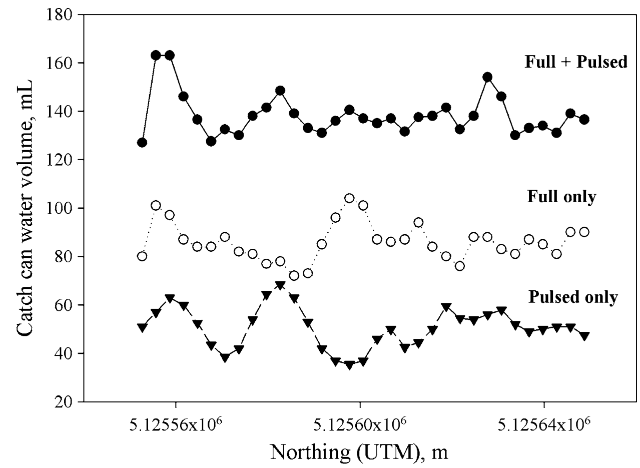

Fig. 13 Full and pulsed water application volumes by location

This “mapfile” is a file containing a grid of solenoid “On-Time” values, on a 1 m× 1 m cells, based on a 60-s irrigation duty cycle; thus the percent correction values were transformed into seconds. The 100% “On-Time” values, i.e., solenoid valves open 60 s out of 60 s, were attributed to the maximum percent correction value, that in average was 10%, while the minimum percent correction value of 16% was given to a solenoid valve opening setting of 74%.

All other corrections were scaled in between the maximum and minimum correction values. The no correction zone corresponded to a 90% “On-Time” value. On June 10, the correction values were applied through the variable irrigation system at 30% PT in order to evaluate the capability of the WSU RIMCS system to deliver the compensation scheme into field H11. Figure 13 shows the results.

In Fig. 13, the lower line (inverted triangle symbols) corresponds to the variable or pulsed irrigation application (Pulsed only series), the middle line (open circle symbols) to the full rate or “uniform” application (Full only series), and the upper line (catch can line 2, close circle symbols) corresponds to the addition of the full application of May 27 with the variable application of June 09 (Full + Pulsed series). The Pulsed only series, in general, applied the opposite water application shape distribution than the application shown by the Full only series. This is an indication that the RIMCS system was able to compensate and deliver more water on the locations that had received less water, and the opposite for the locations that received more water with the “uniform” application. The upper curve, in Fig. 13, shows that the “Full + Pulsed” water amounts display less variability than the Full only or Pulsed only curves, evidence of compensation. Only the first 10 m at the south field position shows a larger discrepancy that may be attributed to the LM gear drive/spans re-alignment process since all irrigation tests were done in the northern (uphill)

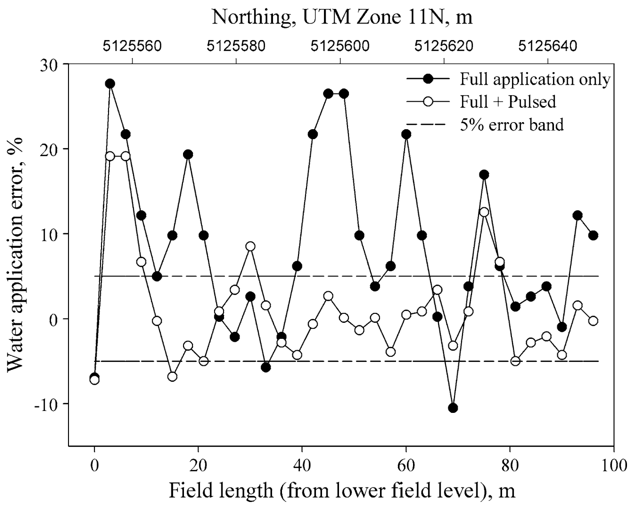

Fig. 14 Full only and "Full + Pulsed" water application errors by location

direction and the system had to be brought downhill (south) at 70% PT, thus affecting the system alignment due to the large change in PT settings (system travel speed).

Figure 14 shows the water application errors in percent for the "Full only" and "Full + Pulsed" series described for Fig. 13. The percent errors for the "Full only" irrigation event fluctuated between −8 and 23%, while the errors for the "Full + Pulsed" series, i.e., the "Full" application plus the correction application through the variable irrigation application (RIMCS) remained mostly in the ±5% zone (5% error band). There were few points outside the 5% zone, other than the ones at the south end of the field explained by the re-alignment process of the LM system. These points falling outside of the 5% zone indicate the need for some refinement on the correction values for those particular locations in the field and they have to do with averaging of the errors.

It is believed that with more irrigation tests at more PT settings the model will be refined and consequently will be able to better compensate for errors in water application and further reduce the water application depth variability. Nevertheless, the CUc value for this particular evaluation test was increased from 93 to 96%; while the distribution uniformity (DU; Keller and Bliesner 1990) was considerably improved from 82.7 to 90.7% (i.e., DU values before and after just one compensating irrigation event, respectively). The DU was calculated considering the average low quarter water depth applied in relation to the overall average water depth applied.

It is speculated that with subsequent compensating irrigations the variability in water depths applied (by location in the field) will be minimized and CUc and DU values would be further improved.

These results are evidence that RIMCS may be a useful tool in compensating inherent water application errors of linear moves and center pivots.

Conclusions

It was shown that the terrain elevation affected the LM cart travel speed, and that changes in the travel speed inversely affected the uniformity of water applied by position in the field. At lower LM irrigation system PT settings, the CUc values were greater, i.e., lower rmse values, thus less water application variability.

The water application percent errors were related to the system location in the field by a polynomial model. The errors, in magnitude and sign, tend to occur more or less in the same location in the field regardless of PT setting and rather because of the LM cart stop/advance pattern. There was evidence of periodicity or repetitiveness on the percent error pattern every 40 or so meters along the travel direction of the LM system.

A method on how to apply correction values to compensate for application errors, by position in the field using a variable irrigation monitoring and control system, was described. This system (RIMCS) reduced the water application error by location from the range −8, +23% to mostly ±5% when pulsing solenoid valves (nozzles) using the compensation scheme or correction values in the system "mapfile." The CUc was increased from 93 to 96% with just one compensation irrigation application event; while DU values improved from 82.7 to 90.7%.

These findings suggest that a LM irrigation system tends to consistently under irrigate the same locations of the field while over irrigating other locations during a cropping season, thus reducing the overall efficiency of the system by decreasing the optimum water and fertilizers uptake levels in the soil profile, which may impact yields and crop quality; or it may affect the environment.

It is expected that with more irrigation tests at different PT settings, the model will be refined to further lower the application errors.

Finally, the methodology presented has to be tested on application errors resulting from variable irrigation when applied by irrigation zones. Furthermore, the methodology has to be expanded to compensate for application errors over the full length of the LM and CP irrigation systems.

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